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Similar but separate systems underlie perceptual bistability in vision and audition

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SD: Study design, data interpretation, writing the ms

DF: Data analysis and interpretation, figures

RvE: Study design, data interpretation, reviewing the ms

MT: Study design, running the experiment (UoP), reviewing the ms

ZK: Running the experiment (RCNS)

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Additional Information

Competing financial interest

The authors have no competing financial interests.

Abstract

The dynamics of perceptual bistability, the phenomenon in which perception switches between different interpretations of an unchanging stimulus, are characterised by very similar properties across a wide range of qualitatively different paradigms. This suggests that perceptual switching may be triggered by some common source. However, it is also possible that perceptual switching may arise from a distributed system, whose components vary according to the specifics of the perceptual experiences involved. Here we used a visual and an auditory task to determine whether individuals show cross-modal commonalities in perceptual switching. We found that individual perceptual switching rates were significantly correlated across modalities. We then asked whether perceptual switching arises from some central (modality-) task-independent process or from a more distributed task-specific system. We found that a log-normal distribution best explained the distribution of perceptual phases in both modalities, suggestive of a combined set of independent processes causing perceptual switching. Modality- and/or task-dependent differences in these distributions, and lack of correlation with the modality-independent central factors tested (ego-resiliency, creativity, and executive function), also point towards perceptual switching arising from a distributed system of similar but independent processes.

Keywords

Ambiguous perception; perceptual rivalry; sequential correlation; bistable perception, modality-specificity, cross-modal correlation

Introduction

Unravelling the perceptual strategies used by the brain to make sense of the world remains an ongoing challenge, not least because people differ both in their intrinsic makeup and life experiences which help to shape their individual information processing systems. A perceptual phenomenon which provides some help in this respect is that of perceptual bi- or multi-stability^{1,2}. Qualitative changes in perceptual experience in response to an unchanging sensory input as well as consistent individual differences in perceptual behaviour³⁻⁶ can provide insights into perceptual grouping and decision-making processes. Although bistability exists in different modalities – visual, auditory, and even olfactory – it remains unknown whether perceptual switches in the different modalities are governed by a central mechanism or by separate, modality-specific systems. Similar fundamental properties of perceptual bistability are observed both in vision and audition^{7,8}, suggesting that common processes may be involved. However, there is little evidence for cross-modal commonality at the individual level. Here, we show that perceptual switching in vision and audition arises from highly similar but independent sources.

The same principles of perceptual alternation, e.g., general properties of exclusivity, inevitability, and stochasticity², and Levelt's propositions^{9,10}, are observed in many different visual paradigms¹¹⁻¹³. Perceptual switching behaviour consistent with these principles is also observed in the auditory modality^{14,15}. These principles have formed the basis for a number of models of perceptual bistability both in vision¹⁶⁻¹⁸ and audition¹⁹. However, in general the models are expressed at a rather abstract level, and are agnostic as to how their processes might map onto brain structures and processing systems.

Brain-imaging studies show a widespread network of areas (primarily in right hemisphere) that typically appear in transition-related contrasts in fMRI studies of visual bistability, including inferior frontal cortex (IFC), dorsolateral prefrontal cortex (DLPFC), frontal eye fields (FEF), temporoparietal junction (TPJ), and intraparietal sulcus (IPS) ²⁰; IPS was also identified in a fMRI study of auditory bistability ²¹. However, there is controversy surrounding interpretation of these findings. Various fMRI studies (e.g., ^{22,23,24}) identified a network of early visual and frontoparietal regions whose activity was time-locked to perceptual switches, but some more recent studies ²⁵⁻²⁹ have suggested that at least the frontal activity may be related to response generation rather than perception. Studies manipulating parietal activity with transcranial magnetic stimulation (TMS) have demonstrated different causal roles for separate parietal sub-regions in perceptual switching, with stimulation of a posterior locus prolonging the time between switches ³⁰ and stimulation of a more anterior locus decreasing it ^{31,32}. As these parietal regions are not strictly visual, the results support the possibility of a distributed, high-level network involved in the control of bistability across modalities. However, application of TMS to non-visual bistability has not yet been reported.

Perceptual switching is typically characterised by the distribution of perceptual phase durations (i.e. periods during which one interpretation is experienced); generally reported as a gamma ⁹ or log-normal distribution ³³. A recent meta-analysis by Cao, et al. ³⁴ showed, furthermore, that perceptual phase durations exhibit so-called scale free properties across many different visual and auditory paradigms. Therefore, they suggested that perceptual switching might best be explained by changes in the combination of discrete states across a finite set of independent processes, such as switches between up and down states in

cortical columns; i.e., a highly distributed system in which the specifics depend on the brain areas involved in the task.

To date, three studies have investigated correlations between perceptual switching in visual and auditory tasks ^{7,14,35}. Small but significant within-individual correlations were reported between visual and auditory perceptual switching in one study ¹⁴. In contrast, Pressnitzer and Hupé ⁷ found that although the general properties of bistability were similar in the two modalities, the number of perceptual switches was not significantly correlated across modalities at the individual level. In their next study ³⁶, participants were required to report their perceptions of the visual and auditory bistable stimuli concurrently. They found no significant evidence that switching in one modality predicted switching in the other. To some extent these data favour interpretation in terms of a distributed system of perceptual switching, but the results so far are somewhat equivocal.

In the present study we aimed to compare perceptual switching behaviour within individuals using the visual ambiguous structure-from-motion ³⁷ and auditory streaming ³⁸ tasks. In the experiment reported in the main text, participants were required to classify their perceptions using two perceptual categories (bistability); in the supplementary material we report a three-category (multistable) version of the experiment.

Support for a distributed stimulus-driven system might be found if any of the commonalities are present by default and not as a result of some central process like attention. If a central system sensitive to top-down effects is an important source of commonality between visual and auditory perceptual switching, then we would expect to observe far higher correlations across modalities when participants are asked to bias their perception in some way, than in a neutral condition, because the instruction to bias leads to tighter top-down control, which

would affect the central switching mechanism. A combination of top-down and stimulus-driven effects have been assumed in some previous models of bistability; e.g. ^{39,40}.

Therefore, we correlated individual switching rates across modalities in three conditions, a Neutral condition, and two biased conditions (Hold – participants were asked to hold onto each percept for as long as possible, and Switch – participants were asked to switch as quickly as possible between alternative percepts).

Another possible central source of correlation would be some form of switching control centre generating switching signals that are fed back down to the sensory areas, as suggested by some of the brain imaging and manipulation studies, reviewed above. If there is such a modality-independent central switch generator involved (previous evidence has been specifically for vision), then we would expect the properties of perceptual switching in the two modalities to be very similar indeed, right down to the detailed level of perceptual phase distributions. Finding correlations between perceptual switching behaviour and modality-neutral central factors, such as ego-resiliency, creativity, or executive function, would also be consistent with a central, modality-independent source of switching.

Finally, a different source of commonality may lie at the microcircuit level, conceptually hypothesised previously in computational theories ^{16,17}, and recently supported by the analysis and model of Cao, et al. ³⁴. Common microcircuit properties across the different sensory modalities within an individual could produce similar switching properties across tasks and modalities. However, while there may be strong similarities in perceptual switching behaviour overall, we would expect there to be observable differences at the detailed level of perceptual phase distributions. To distinguish between the central and distributed system hypotheses, we analysed the phase duration data in detail. First, we

established the type of distribution that best characterised the phase durations in each modality. Next, we calculated the parameters describing those distributions. Finally, at the most detailed level of comparison, we examined the relationships between successive phase durations at a range of lags.

Results

Condition and modality

The influence of the attentional manipulation and modality on the average number of switches was assessed using a 2 (modality: visual, auditory) x 3 (condition: Neutral, Hold, Switch) repeated-measures analysis of variance (rmANOVA; the Greenhouse-Geisser correction was applied to violations of sphericity). The main effect of condition was significant ($F(2,64) = 27.182, p < .001, \eta^2_{\text{partial}} = .459, \epsilon = .581$). This shows that participants were able to bias their perception according to instructions, leading to longer durations in the Hold condition and shorter durations in the Switch condition, compared to the Neutral condition (Figure 1). Neither the effect of modality ($F(1,32) = 2.060, p = .161$) nor the modality/condition interaction ($F(2,63) = 1.252, p = .287$) were significant. Thus, participants switched similarly across modalities (possibly due to the choice of stimulus parameters rather than inherent cross-modal commonalities; e.g., in visual bistability (Necker cube), switching rates decrease with increasing stimulus size ³⁹, in auditory streaming, switching rates decrease with increasing frequency difference and with decreasing presentation rate ⁴¹), and the effect of attentional bias was similar for the two modalities.

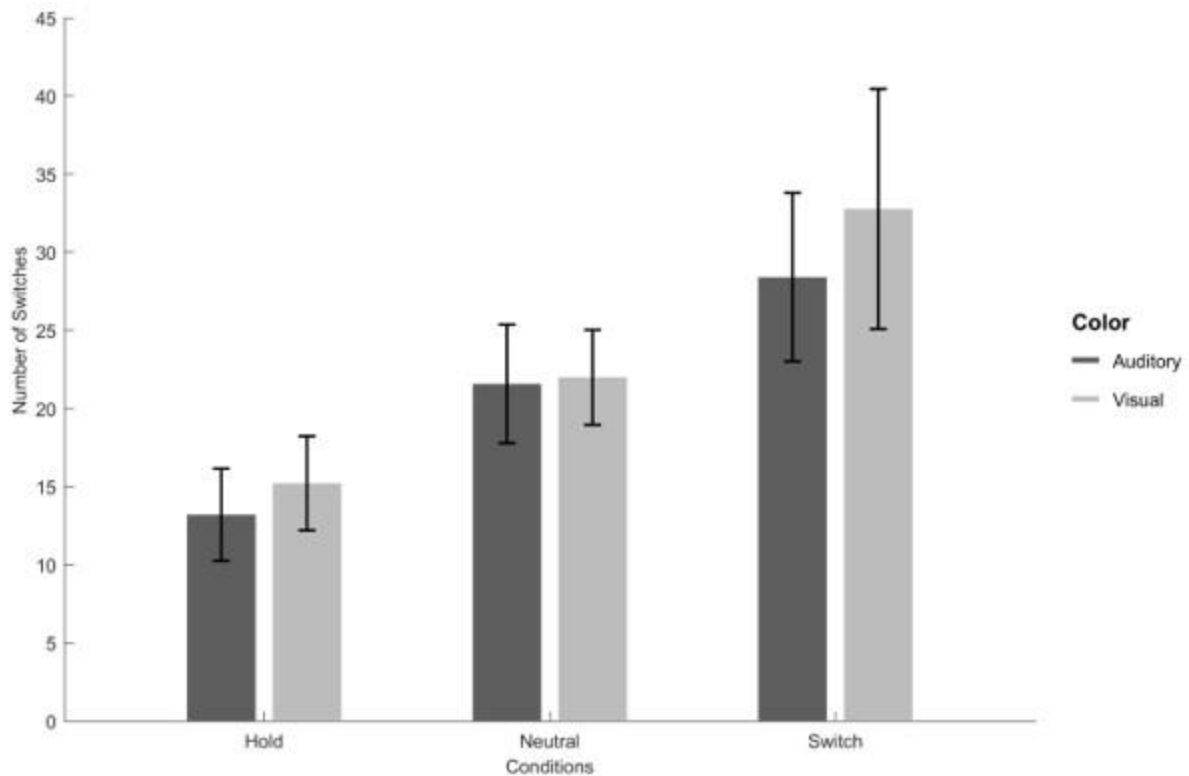


Figure 1. Mean number of perceptual switches during a 180-second block in each condition and modality. Error bars indicate 95% confidence intervals.

Correlations across modalities

Cross-modal relationships between number of switches were tested with Pearson correlations separately for each condition (Figure 2). Correlations between the two modalities were significant in all three conditions: Neutral ($r(33) = .456$, $p = .008$, $CI_{95} = .134-.691$), Hold ($r(33) = .550$, $p = .001$, $CI_{95} = .255-.752$), and Switch ($r(33) = .626$, $p < .001$, $CI_{95} = .361-.798$). The correlation coefficients observed for the Hold ($z = -0.490$, $p = .624$) and Switch ($z = -0.940$, $p = .347$) conditions did not significantly differ from those of the Neutral condition. The correlation observed in the Neutral condition is not significantly different ($z = 0.238$, $p = .782$) from the auditory-visual correlation ($r(23) = .400$, $p = .060$, $r^2 = .160$) reported by Pressnitzer and Hupé ⁷. No significant correlations were found between the

number of switches in the Neutral condition and any measures in the creativity, ego-resiliency, and Stroop tasks.

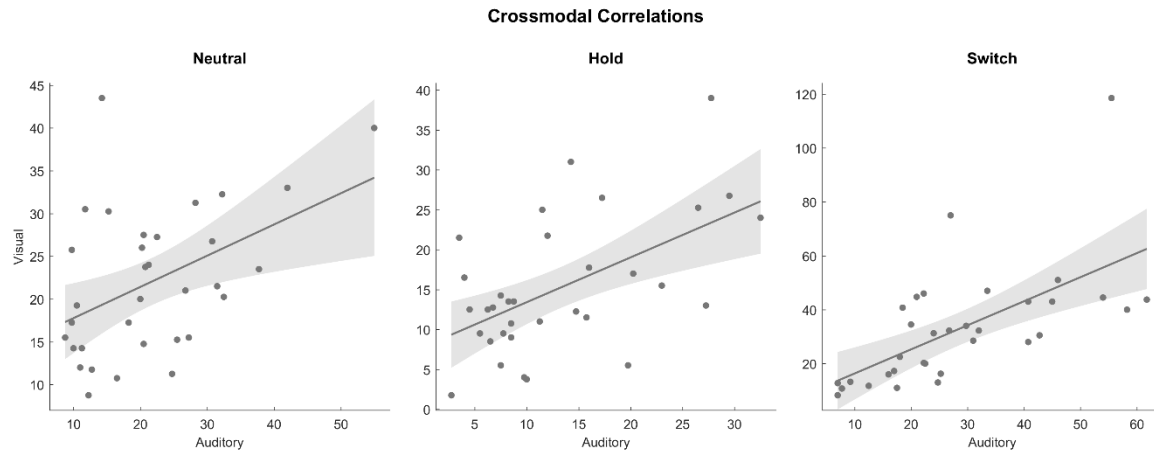


Figure 2. Correlations in the number of perceptual switches across modalities, separately for each condition; shading indicates 95% confidence intervals of the slope of the regression line.

Individual consistency

We restricted the rest of our analyses to the Neutral data as the correlations between switching in the visual and auditory task did not differ between the neutral and biased conditions and there was no modality \times bias interaction in the ANOVA, allowing us to assume that similar processes are at work in the neutral and biased conditions.

To explore individual consistency in switching across modalities, percepts were first reorganized into dominant/non-dominant categories (i.e., percepts were relabelled block-by-block according to their dominance to allow comparisons between the two modalities). We then constructed participant transition matrices⁴² from the relabelled data (see Supplementary Material for details). Intra-modal consistency was measured as the Kullback-Leibler (K-L)⁴³ divergence between participants' auditory and visual transition matrices. Inter-participant consistency was measured by comparing the K-L distances between a

participant's transition matrices and the transition matrices of all other participants. The distributions of intra-modal and inter-participant distance measures were compared using a one-tailed Wilcoxon's Rank Sum test. The result of the test ($z = -2.913$, $p = .002$) indicates that participants' perceptual switching behaviour is more similar across the two modalities ($M = .042$, $CI_{95} = .028-.057$) than the variation across participants ($M = .093$, $CI_{95} = .088-.098$). In short, participants responded consistently within and across modalities.

Comparison of the distributions of phase durations across modalities

Raw phase durations from the Neutral condition were pooled across participants separately for each modality. First, we tested whether the distribution of the phase durations was gamma or log-normal. Examination of Q-Q-plots⁴⁴ indicated that the log-normal distribution fits our data better than the gamma distribution (Figure 3). The Akaike Information AIC,⁴⁵ also indicated that the log-normal distribution fits the data better than gamma for both the auditory ($AIC_{\text{log-normal}} = 16474$, $AIC_{\text{gamma}} = 17024$) and visual ($AIC_{\text{log-normal}} = 17070$, $AIC_{\text{gamma}} = 17504$) modalities.

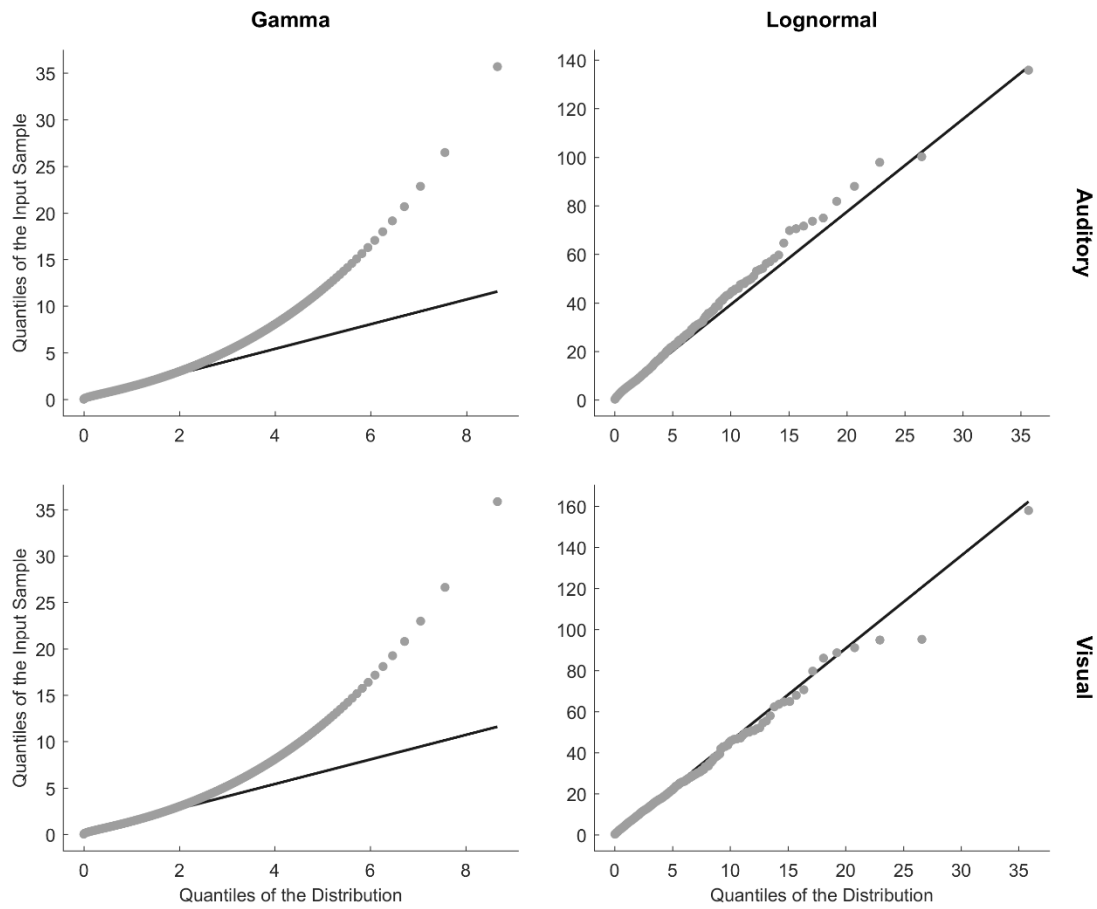


Figure 3. QQ-plots of gamma (left) and log-normal (right) distributions for phase durations from the Neutral conditions in the auditory (upper row) and visual (lower row) modalities.

We then compared the auditory and visual phase distributions in two steps. First, phase distributions from the two modalities were compared using a Two-Sample Kolmogorov-Smirnov test. The result indicated that the auditory and visual distributions were significantly different ($D = .047, p = .003$). Second, to examine the factors underlying this difference, the mu and sigma parameters of the log-normal distributions (which determine the central tendency and variance, respectively), were calculated for phase durations separately for the auditory and visual modalities with 95% confidence intervals (Figure 4). While the confidence intervals of the mu parameter overlap across the two modalities, the

confidence intervals of the sigma parameter do not. This shows that although phase durations in the auditory and visual modalities can both be described by the same type of distribution (log-normal), the details of the distributions are different.

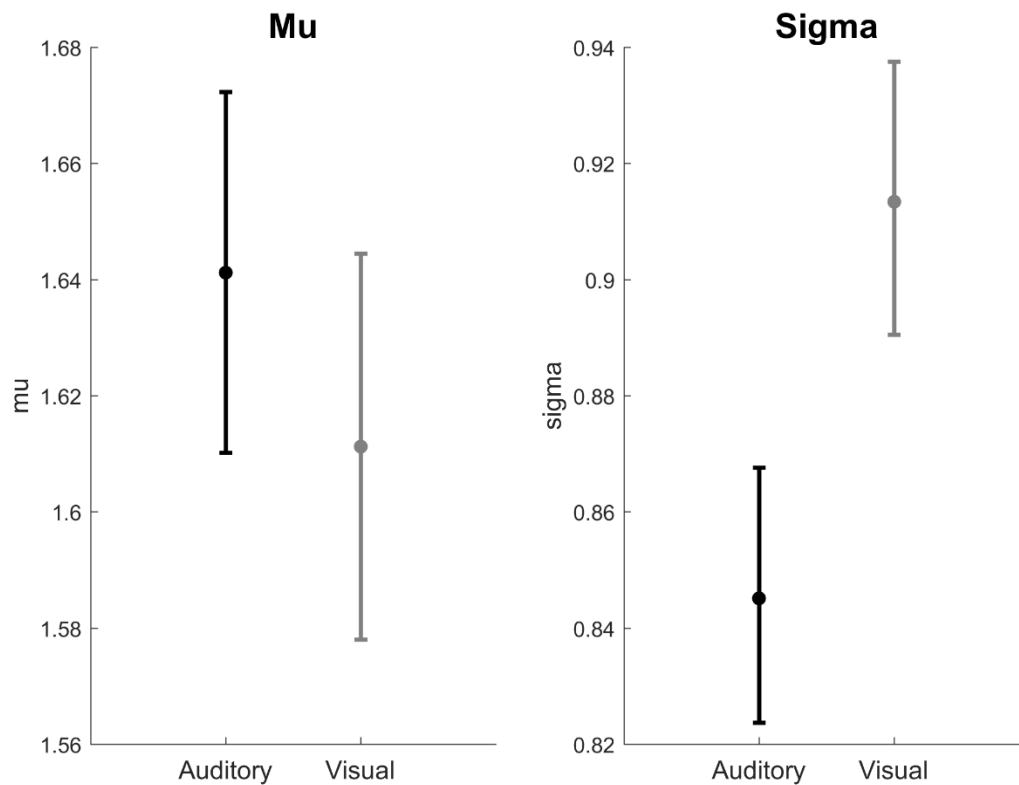


Figure 4. *Mu and Sigma parameters of the log-normal distribution with 95% confidence intervals.*

Correlations between successive phases

Relationships between the duration of each perceptual phase and the durations of perceptual phases at one, two and three lags were tested with a mixed-level linear regression where participant identity was included as a random effect. Raw phase durations from the Neutral condition were \log_{10} -corrected in accordance with their log-normal

distribution. This allowed us to meet not only the normality but also the linearity and heteroscedasticity assumptions of the test. All lags were significant in the auditory modality, whereas non-significant models were observed for the visual modality in half of the cases. The explained variance (R^2) is higher, whereas the Akaike (AIC) and Bayesian Information Criterion (BIC) values are lower for the auditory modality compared to the visual modality; see (Table 1).

Modality	Transition	Lag	R^2	AIC	BIC	Unstandardized b	t	r
Auditory	D/ND	#1	20.27%	512.75	533.10	.249 (.197-.300)	9.516***	.450
		#2	20.34%	625.13	645.48	.186 (.132-.240)	6.775***	.451
		#3	13.71%	583.16	603.52	.092 (.039-.144)	3.407**	.370
	ND/D	#1	21.36%	712.49	732.89	.240 (.183-.298)	8.208***	.462
		#2	13.97%	578.63	599.03	.155 (.100-.209)	5.588***	.374
		#3	20.30%	653.81	674.21	.153 (.096-.209)	5.337***	.451
Visual	D/ND	#1	14.85%	829.93	850.37	.149 (.100-.199)	5.940***	.385
		#2	5.77%	1158.48	1178.91	.239 (.184-.293)	8.652***	.240
		#3	13.48%	909.05	929.48	-.023 (-.074-.028)	-0.878	.361
	ND/D	#1	10.68%	1147.29	1167.75	.147 (.085-.208)	4.648***	.327
		#2	14.05%	885.74	906.21	.060 (.005-.116)	2.131*	.375
		#3	8.29%	1151.43	1171.89	.037 (-.025-.098)	1.156	.288

Table 1. Relationship between successive phase durations in the auditory and visual modalities. “Transition” refers either to the Dominant/Non-Dominant (D/ND) or the Non-Dominant/Dominant (ND/D) transitions. “Lag” refers to the number of intervening percept durations: for example, lag 1 refers to the correlation with the percept duration immediately following each individual duration. R^2 refers to the explained variance of the model, whereas AIC and BIC refer to the Akaike or Bayesian Information Criterion, respectively. “Unstandardized b ” refers to the slope of the model with CI_{95} values included in parenthesis. “ t ” refers to the t -test examining the slope’s difference from zero and asterisks are indicating the level of significance (*** $p < .001$, ** $p < .01$, * $p < .05$). “ r ” refers to the correlation coefficient between the two phases estimated from the R^2 .

Discussion

Our aim was to investigate commonalities between visual and auditory bistability using two well-studied exemplar tasks, visual ambiguous structure-from-motion and auditory streaming. We found strong similarities in the perceptual switching behaviour of individuals across modalities when viewed at a coarse level of description, but differences when viewed at a finer level of detail.

The main evidence for similarity comes from the strong correlations between the number of switches participants reported over the same duration in the visual and auditory tasks in all three conditions (Neutral, Hold and Switch). The correlations we found in the Neutral condition do not differ significantly from those reported by Pressnitzer and Hupé ⁷, although in our study the correlation reached statistical significance, presumably thanks to the greater statistical power afforded by our larger sample. In accord with this finding, comparisons of the transition matrices (which can be used to characterise perceptual switching behaviour at a finer level of detail than the gross number of perceptual switches Denham, et al. ⁴²) showed that individual participants were consistent in their behaviour across blocks and across modalities, despite the well-known stochasticity of perceptual bistability. Furthermore, attentional manipulations affected perceptual switching similarly in both modalities. While the visual-auditory correlations were numerically larger when attentional manipulations were introduced, the differences between the correlations found in the different conditions were not significant, showing that the correlations observed are unlikely to arise principally from some attention-related top-down effect.

The distribution of phase durations in the two modalities was also quite similar. However, in contrast to the assumption of the gamma distribution used in many previous studies

(e.g.,^{2,9,18,46,47}) we observed a log-normal distribution in both modalities. Our observations are consistent with the findings of Rubin and Hupé⁴⁸ and Lehky³³ who also noted that their data was often better fit by a log-normal distribution. While a single, stochastic process would yield a gamma distribution, a log-normal distribution suggests that within each modality, switching is triggered by a multiplicative combination of a set of independent stochastic processes. This provides quite tight constraints on possible architectures. Recent theoretical considerations by Cao, et al.³⁴ have shown that the distributions observed in many bistability experiments are better explained by the combination of a finite set of independently switching processes. The generalised Ehrenfest process they used in their analysis yields a log-normal-like distribution. Our findings are thus consistent with their proposals and have important implications for understanding and modelling the mechanisms underlying perceptual bistability.

Differences between the two modalities were found when the log-normal distributions characterising the phase durations in each modality were examined in more detail. Firstly, we found that the distributions were different (two-sample Kolmogorov Smirnov test). Secondly, we found that while the means of the distributions were similar, the spread (sigma) was not. Together, these findings support the hypothesis that perceptual switching in the two tasks depends on similar but distinct processes.

A similar conclusion emerges from considering the relationships between successive perceptual phases. Successive phase durations have often been assumed to be independent (i.e. consistent with phase durations having a gamma distribution)⁹, and this has influenced both theories and models of bistability (e.g.,^{46,49}). However, more recent work has shown that there are small but significant correlations between successive phases both in vision⁴⁶

and audition ⁵⁰. The relationships we found were larger than those reported previously, likely because of differences in the analysis methods (see the Supplementary material for more details). The finding of significant correlations between successive phase durations points towards some form of memory with longer duration than considered in previous modelling work, something that may be interesting to explore in future work. The relationships between successive phases were higher for the auditory than for the visual data. This reinforces the emerging conclusion that while the very strong similarities between perceptual bistability in vision and audition imply that perceptual switching is generated in a very similar way in the two modalities, nevertheless, the precise source of switching differs.

There was no correlation between perceptual switching and any of the modality-neutral central factors tested (creativity, ego-resiliency, and executive function). While the absence of correlations with these tasks is not evidence of a distributed system, these findings certainly provide no support for a unified central source of switching. Since we have only used one exemplar task in each modality, we cannot distinguish between the existence of modality-dependent sources of switching, or a more distributed system in which switching arises from task-dependent sources. However, the log-normal distribution of perceptual phases that we found does point toward the latter interpretation. We also make no any specific claims about what the underlying mechanisms might be; adaptation, increased inhibition, increased noise are all possibilities, but our experiment was not designed to distinguish between them. Thus, one possible extension of the current research is to test what roles each of these mechanisms might play in a distributed system such as that indicated by our results

Conclusion

Fundamentally similar properties characterise both auditory and visual perceptual bistability suggesting that the way perceptual switching is generated is very similar in both modalities. However, differences in the details of the phase distributions argue against a modality-independent central switch generator. Rather, they suggest a more distributed system in which switching is generated in very similar ways in different brain areas. Individual consistency within and across modalities, as well as the fact that the best fit function for describing the distribution is log-normal, suggest that generic circuit properties rather than purely stochastic processes, may lie at the heart of the switching process.

Method

Experimental Design

We adopted a mixed design in which each participant took part in one session. A complete session consisted of preliminary procedures followed by a period of training and three experimental conditions interleaved with a set of supplementary tasks; the experimental design is summarised in Table 2 below. Experimental conditions were distinguished by the task instructions given to participants: Neutral (should not try to influence their perceptions), Hold (should try to hold onto each percept they experienced for as long as possible), and Switch (should try to switch to a new percept as quickly as possible). Each condition comprised eight stimulus blocks, four visual (V) and four auditory (A). In the visual task, participants were asked to report the direction of motion of the front face of a rotating sphere (ambiguous structure-from-motion), while in the auditory task, they were asked to report on the perceptual grouping of tones in a sequence (auditory streaming). In the

experiment reported here, participants were asked to report their perceptions using two perceptual categories. In the supplementary material we report a similar experiment in which participants were asked to report their perceptions using three perceptual categories; the principal effects are the same for both.

Stage	Activity	Description
1	Preliminary steps	Consent, handedness questionnaire ⁵¹ , hearing check
2	Training <ul style="list-style-type: none"> - Visual task - Auditory task 	Response categories LEFT, RIGHT INTEGRATED, SEGREGATED
3	Test Condition 1: Neutral	8 stimulus blocks: VVVVAAAA (AAAAVVVV)
4	Supplementary activity	Ego-resiliency questionnaire, (creativity questionnaire, Stroop task)
5	Test Condition 2: Hold (Switch)	8 stimulus blocks: VVVVAAAA (AAAAVVVV)
6	Supplementary activity	Creativity questionnaire (Stroop task, ego-resiliency questionnaire)
7	Test Condition 3: Switch (Hold)	8 stimulus blocks: VVVVAAAA (AAAAVVVV)
8	Supplementary activity	Stroop task (ego-resiliency questionnaire, creativity questionnaire)

Table 2. *Experimental design, showing the eight stages in an experimental session. The order of the following was counterbalanced across participants: a) modality ordering of stimulus blocks, VVVVAAAA or AAAAVVVV, b) biased test conditions Hold/Switch in stages 5 and 7, c) supplementary task order ego-resiliency/creativity/Stroop in stages 4, 6 and 8.*

Participants

The study was run at two separate locations (Hungary: Research Centre for Natural Sciences of the Hungarian Academy of Sciences (RCNS); U.K.: University of Plymouth (UoP)), partly for

practical reasons, and partly to reduce the risk of biasing the data by the specifics of the labs or their personnel. A total of 44 adults participated in this study (RCNS, 24 adults: 18 females, $M_{age} = 21.5$, $SD_{age} = 1.98$; UoP, 20 adults: 16 females, $M_{age} = 22.9$, $SD_{age} = 9.52$). The study was approved by the local ethics committee (Hungary: Unified Committee for Psychological Research Ethics (EPKEB); U.K.: Faculty of Health and Human Sciences Research Ethics Sub Committee, University of Plymouth). The research was performed in accordance with relevant regulations. Informed consent was obtained from each participant prior to beginning the experiment. All participants had normal or corrected-to-normal vision and normal hearing, and gave written informed consent. Participants received modest payment or course credits in return for their participation.

Training

Visual Task

Participants viewed 500 dots (each subtending a viewing angle of 4.7 arcmin) projected onto a computer screen. The dots' position changed from one frame to the next as if they were located at random positions on a rotating sphere, which subtended a viewing angle of 3.3 degrees. A chin rest was used to fix the distance of the head relative to the screen. At RCNS, the visual stimuli were presented on a Samsung 17" TFT 740B screen with a resolution of 1280 x 1024 pixels, and at UoP on a Dell screen with a resolution of 1920 x 1080 pixels; stimulus parameters were adjusted to generate the same size sphere (same viewing angle) for the same screen to chin-rest distance. The virtual sphere rotated about a central vertical axis at an angular velocity of 75 degrees/second. Due to structure-from-motion effects, the moving dots create a vivid impression of a three-dimensional rotating sphere³⁷. Because

there are no depth cues indicating which dots belong to the front or the back of the sphere, the direction in which the sphere rotates is ambiguous, and alternates periodically.

Participants were instructed to report LEFT (by holding down a key) for as long as they perceived the front face of the rotating sphere moving leftwards, and RIGHT (by holding down a different key) for as long as they perceived it moving rightwards. These interpretations were demonstrated to participants using disambiguated examples (see Training Procedure, below). The corresponding mnemonics shown in Figure 5 were used as reminders. The “Enter” and “Shift” keys located on the right-hand side of a standard computer keyboard were used as response keys, with key-response assignment counterbalanced across participants.



Figure 5. *Mnemonics for the perceptual interpretations of the ambiguous structure-from-motion stimulus; LEFT, RIGHT and the key assignment.*

Auditory Task

Participants listened to a cyclically repeating sequence of tones, ordered low-high-low, with a brief gap before repeating (LHL_LHL_..), according to the auditory streaming paradigm³⁸. Sinusoidal tones of 75 milliseconds (ms) duration were used; the frequency of the L tone was 400 Hz and the H tone was 504 Hz, a difference of 4 semitones. The stimulus onset asynchrony (SOA, onset to onset time interval) was 125 ms. The sounds were delivered

through Sennheiser HD600 headphones at both locations. Most commonly, listeners either perceive this sequence as if all tones belong together, termed INTEGRATED (i.e., they form a single coherent sound stream with a typical galloping rhythm caused by the triplet pattern), or they hear the tones splitting apart into two separate isochronous streams of sounds, L_L_L .. and H__H__H., termed SEGREGATED.

Participants were instructed to report INTEGRATED (by holding down a key) for as long as they perceived a single coherent sound stream and SEGREGATED (by holding down a different key) for as long as they perceived two streams, one containing low and the other high tones. These interpretations were demonstrated to participants using disambiguated examples (see Training Procedure, below). The corresponding mnemonics shown in Figure 6 were used as reminders. The “Enter” and “Shift” keys located on the right-hand side of a standard computer keyboard were used as response keys, with key-response assignment counterbalanced across participants.

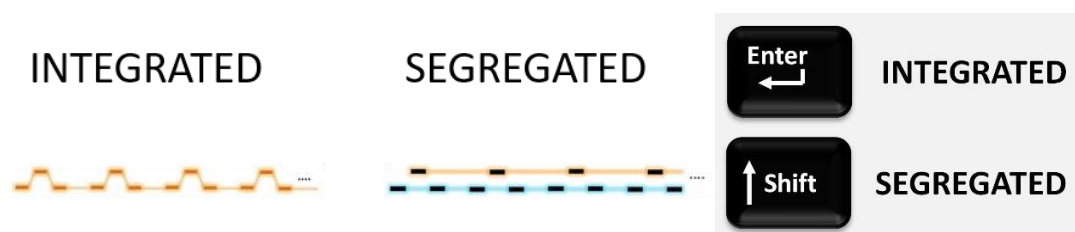


Figure 6. *Mnemonics for the perceptual interpretations of the tone sequence; INTEGRATED, SEGREGATED, and the key assignment.*

Training Procedure

Training in the two modalities was carried out separately, using a standardized procedure to ensure consistency. First, the perceptual categories were explained and demonstrated using stimuli in which the relevant category was disambiguated (visual disambiguation: to bias

perception towards LEFT (RIGHT), luminance of rightward (leftward) moving dots was reduced; auditory disambiguation: to bias perception towards INTEGRATION (SEGREGATION), frequency difference between L and H tones was reduced (increased) to 1 (H = 424 Hz) and 10 (H = 713 Hz) semitones, respectively). Next, participants practiced continuously responding to 60-second versions of the test stimuli to each of which a short segment of a disambiguated sequence was concatenated; feedback on the proportion of time they correctly categorised the disambiguated section was provided. They also practised categorising sequences formed only from concatenated disambiguated stimuli, with feedback on the proportion of correct categorisation for each segment. Once participants understood and could easily categorise their perceptions, they proceeded to the test phase. No participant was rejected because they failed to understand the training requirements.

Testing

The main experiment consisted of three conditions. In each condition, there were four contiguous 180-second visual blocks and four contiguous 180-second auditory blocks (VVVVAAAA or AAAAVVVV), with order counterbalanced across participants. At the end of each test block, there was an eight-second long disambiguated segment randomly chosen from LEFT, RIGHT (for visual) or INTEGRATED, SEGREGATED (for auditory). Responses to the disambiguated segments were used to monitor participant performance. A key press initiated the start of each block, so it was possible for participants to take short breaks between blocks. The initiating key press triggered an instruction screen sequence that prepared them for the block; this consisted of a 1s blank screen, followed by a 10s instruction screen showing category mnemonics and key assignment, then a 2s blank screen followed by a 2s central fixation cross before the stimuli for the block commenced.

Conditions

Conditions were defined by differences in the task instructions. In the Neutral instruction condition (which always ran first, to avoid carry-over effects from the other two conditions), participants were asked to report their perceptions without trying to influence them in any way. In the Hold condition, participants were asked to report their perceptions while at the same time trying to hold onto each percept for as long as possible. In the Switch condition, participants were asked to report their perceptions while at the same time trying to switch to a new percept as quickly as possible. The order of the Hold and Switch conditions were counterbalanced across participants. Instruction screens reminded participants of their current task.

Data extraction

Perceptual reports were recorded by polling the key status every 10ms for the duration of the stimulus, and the resulting data were processed to extract the sequences of continuous periods during which the same perceptual category was reported. This resulted in a sequence of perceptual phases together with the start time for each, relative to the start of the stimulus. The reports from the disambiguated segments were extracted separately and used as a measure of how well a participant understood the perceptual categories and the key assignments. To allow for a delay in reacting to the stimulus change ⁵², the first two seconds of each disambiguated segment were ignored. Any participant who scored an average of less than 30% in a category, or less than 60% over both categories was excluded from further analysis. 11 participants were excluded from the analysis based on poor categorisation of disambiguated segments. Exclusion is based on a previous study ⁵³ showing, for the auditory task, that participants who correctly labelled the disambiguated segments showed greater

internal consistency overall. The analysis reported here is based on 33 participants (25 females; 19–25 years; $M_{\text{age}} = 21.45$, $SD_{\text{age}} = 1.82$). The rejection rate is similar to previous studies using the same procedure^{54,55}. For the analysis, we used the number of perceptual switches in each block and the phase durations.

Supplementary tasks and data analysis

Full details of each of the supplementary tasks (the ego-resiliency and creativity questionnaires, and the Stroop task) and the data analysis are reported in the Supplementary Material.

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Additional Information

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Supplementary Material for:

Similar but separate systems underlie perceptual bistability in vision and audition

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This document contains further details of the methods for the experiment reported in the main paper and an outlier analysis and discussion of the successive phase duration correlations for that experiment. It also describes a second experiment, much like that reported in the main paper, in which the number of perceptual alternatives available to participants was increased to three.

Method

This section contains details of the supplementary Stroop task, the ego-resiliency and creativity questionnaires, and the data analysis.

Supplementary tasks

Stroop task

Participants' inhibitory control was measured using a computerized version of the Stroop task¹. Words, coloured red, green or blue, were presented on the same screen used for the experiment, and subtended a vertical angle of 0.9 degrees and a horizontal angle of 3.3-4.7 degrees (the horizontal angle changing with word length). Participants were instructed to respond as quickly and accurately as possible using the arrow keys with their dominant hand on a standard computer keyboard mapped as follows: ↑ for red, ← for blue, and → for green. Stimuli were shown on the screen until one of the response keys was depressed. Each response was followed by a blank screen for 250 ms.

The task consisted of three conditions. In each condition, there were 60 trials. Condition 1 was the neutral-word condition; the names of the three colours (red, blue and green) appeared on a white screen written in black. Participants were required to press the arrow

key corresponding to the colour name. Condition 2 was the neutral-colour condition; four X's appeared on the screen in one of the three colours and participants had to press the arrow key corresponding to the colour of the X's. Condition 3 was the congruent-incongruent condition; colour names appeared on the screen either in the corresponding colour (e.g. "red" coloured red) – Congruent trial, or in one of the other two colours (e.g. "red" coloured blue) – Incongruent trial. Participants were required to press the arrow key corresponding to the colour of the letters (not the word). There were equal numbers of Congruent and Incongruent trials, with order separately randomised for each participant. The Congruent/Incongruent condition received two blocks of 60 trials.

The Stroop interference effect was measured as the difference between the median reaction times of the correct responses in the congruent condition and the median reaction time of the correct responses in the incongruent conditions. Thus, a smaller reaction time difference indicates stronger inhibitory control of a prepotent response.

Ego-resiliency questionnaire

The paper-based ER89 questionnaire² was used to measure ego-resiliency (ER) at UoP. ER89 has 14 items (e.g. ("I like to do new and different things" and "My daily life is full of things that keep me interested"). Participants were instructed to indicate to what extent each item applied to them on a four-level Likert scale from "Does not apply to me at all" to "Applies to me very much". In the Hungarian version³, ER was measured using 11 items from the ER89 questionnaire. For consistency the UoP scores were calculated using the same 11 items. Cronbach's α was 0.671 across all participants. The ER score for each participant is calculated by averaging the score of the eleven items per participant.

Creative behaviour questionnaire

The paper-based Biographical Inventory of Creative Behaviours (BICB) ⁴ was used as a measure of individual creativity. BICB is a 34-item questionnaire, in which participants are instructed to indicate whether they have participated in various creative activities (e.g., “Invented a game or other form of entertainment”, “Composed a poem”, “Started a club, association or group”). Participants were asked to tick all the items that applied to them. The BICB score for each participant is the number of items they ticked.

Data Analysis

To ensure compatibility with previous research, durations of phases during which no response was recorded were merged with the following perceptual pattern. (22 (20)¹ participants did not report any no-responses longer than 300ms, and for those that did, there was no difference in the probability of no-response across conditions and modalities). The number of switches was calculated separately for each block and the scores were averaged across participants separately for each condition and modality. This measure was used to test the effect of attentional manipulations with a repeated measures ANOVA and the connection between modalities with Pearson’s correlation. Correlations were compared to each other using Fisher’s r to z test⁵. For all further analysis, only the data from the Neutral condition were used. The reason for this is that our main effect (the correlation between auditory and visual modalities) was not different between voluntary and neutral

¹ X(Y) indicates the number of participants in the experiment reported in the main paper (and in the experiment reported in this document).

conditions. Thus, the same effects should be observed in further analyses. Repeating all analyses for each condition complicates the results unnecessarily.

For the phase distribution analysis, the last percept in each block was omitted from the analysis, because they were terminated by the end of the block and not by the participant. Phase durations were pooled from all participants separately for each modality. Quantiles of the data were tested against quantiles of gamma and lognormal distributions with Q-Q plots⁶ separately for the two modalities. Phase distributions from the auditory and visual modality were compared using a Two Sample Kolmogorov-Smirnov test ⁷. In addition, the parameters of the distributions were estimated from the data with 95% confidence intervals and the two modalities were also compared based on the similarity of their parameters.

For the phase correlation and intra-modal consistency analysis, percepts were relabelled block-by-block according to their dominance to allow more detailed comparisons between the two modalities; the percept with the larger proportion in a block was labelled as dominant and the other was labelled as non-dominant. This was required to be able to compare the perceptual patterns between modalities. For the phase correlation analysis, we analysed transitions starting from dominant to non-dominant and those starting from non-dominant to dominant separately using data pooled from all participants. The relationship between each phase duration and the following three phase durations was tested using a mixed-effects linear regression separately for the three lags. Participant identity was included as a random variable in the model. R^2 was used to examine the explained variance of each model, whereas the Akaike (AIC) and Bayesian Information Criterion (BIC) were used for model comparison.

For the intra-modal consistency analysis, transition matrices, containing the conditional probabilities for transitions between perceptual alternatives, were constructed from the perceptual reports using the method described in Denham, et al. ⁸. Transition matrices had three rows and columns, one for each perceptual alternative. Each element represents the conditional probability to switch from the starting percept (column) to the percept assigned to the row. A number of transition matrices were built. Firstly, all the data was pooled to calculate a global transition matrix. Next, transition matrices were calculated for each modality separately. Next, transition matrices were calculated separately for each modality for each participant, which will be referred as a participant transition matrix. Finally, transition matrices were also constructed for each block. Denham, et al. ⁸ showed that unobserved transitions from a transition matrix can be estimated from a transition matrix one above in the hierarchy. For example, an unobserved transition in a block transition matrix can be substituted with the corresponding value from the participant transition matrix.

Multi-dimensional outliers in the correlations

Multi-dimensional outliers that can influence the correlation were identified using the following tests and criteria: Mahalanobis distance (13.28, Barnett & Lewis, 1994), Cook distances (1, Cook & Weisberg, 1994), and Centered Leverage values (three times the fraction of the number of tested variables and sample size, which is .182 in our case, Stevens, 2012).

In the Neutral condition, no outliers were indicated by the Mahalanobis (max = 6.314) and Cook (max = 0.768) distances. However, there was a Centered Leverage value higher than

the threshold (0.197). Without this possible influential multi-dimensional outlier, the correlation would be non-significantly higher than the one reported in the main text ($r(32) = .577, p = .001, z = 0.640, p = .522$). In the Hold condition similarly to the neutral, the Mahalanobis (max = 7.833) and Cook (max = 0.155) distances indicated no multi-dimensional outliers, but one participant had a Centered Level value higher than the threshold (0.245). The correlation without this participant would be non-significantly lower than the one reported in the main text ($r(32) = .478, p = .006, z = -0.380, p = .704$). In the Switch condition, only the Cook distance indicated no outliers (max = .868), but one multi-dimensional outlier was indicated by both the participant's the Mahalanobis distance (15.659) and the Centered Leverage value (0.489). The correlation without this participant would be non-significantly lower than the one reported in the main text ($r(32) = .598, p < .001, z = -0.170, p = .865$).

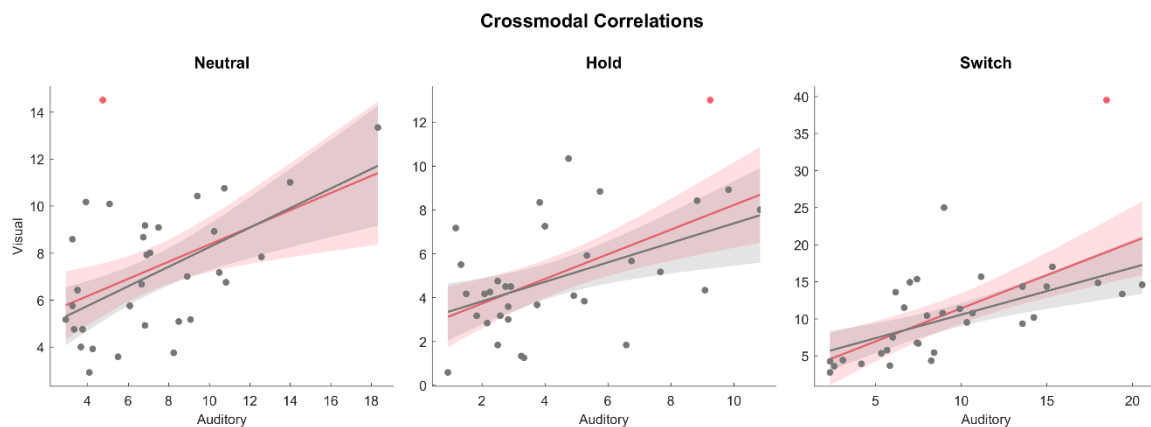


Figure SM1. Correlations in the number of perceptual switches across modalities, separately for each condition. The red dot indicates the outlier participant, while grey dots indicate other participants; grey (pink) shading indicates 95% confidence intervals of the slope of the regression line with (without) the outlier participant.

Barnett, V., & Lewis, T. (1994). Outliers in statistical data (Vol. 3). New York: Wiley.

Cook, R. D., & Weisberg, S. (1982). Residuals and influence in regression.

Stevens, J. P. (2012). Applied multivariate statistics for the social sciences. Routledge.

Further consideration of the successive phase correlations

Although the correlations we find are larger than those reported previously ^{9,10}, much of the difference can be ascribed to the use of the \log_{10} -correction. The plots in Figure SM2 were created by pooling all phase durations from all participants. This resembles the method used by Barniv and Nelken ⁹ and is different from the permutation-based method we adopted in the main text. The non-corrected scatterplots are highly similar to the ones reported by Barniv and Nelken ⁹. It is also very clear that the non-corrected data does not meet the linearity and heteroscedasticity assumptions of Pearson correlation, whereas the \log_{10} -corrected data does. Once more the importance of the log-normal distribution is demonstrated, providing strong support for a distributed system of independent processes underlying perceptual switching.

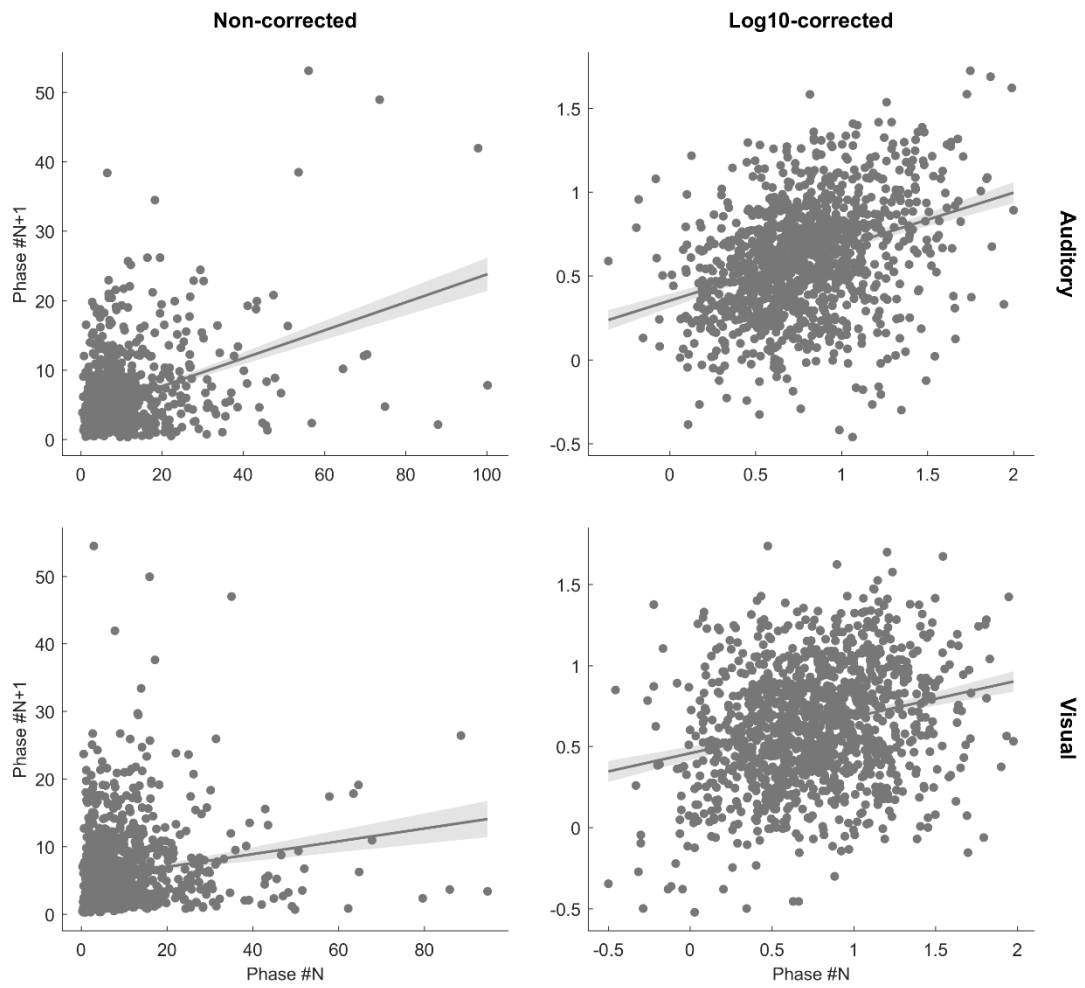


Figure SM2. Successive phase correlations of the dominant/non-dominant transitions at lag 1 separately for the auditory (top panels) and visual (bottom panels) modalities. On the left side, data was plotted without any correction, whereas on the right side, \log_{10} -corrected data are depicted. 95% confidence intervals are indicated by shading.

Experiment 2

In this section we describe a second experiment, just like the first, in which participants were asked to categorise their perceptions according to three instead of two perceptual alternatives. The method is mostly the same as that described for the first experiment, so here we only include details where the method differs.

Experimental Design

Table SM1 illustrates the time course of an experimental session.

Stage	Activity	Description
1	Preliminary steps	Consent, handedness questionnaire, hearing test
2	Training <ul style="list-style-type: none">- Visual task- Auditory task	Response categories LEFT, RIGHT, COMBINED) INTEGRATED, SEGREGATED, COMBINED
3	Test Condition 1: Neutral	8 stimulus blocks: VVVVAAAA (AAAAVVVV)
4	Supplementary activity	Ego-resiliency questionnaire, (creativity questionnaire, Stroop task)
5	Test Condition 2: Hold (Switch)	8 stimulus blocks: VVVVAAAA (AAAAVVVV)
6	Supplementary activity	Creativity questionnaire (Stroop task, ego-resiliency questionnaire)
7	Test Condition 3: Switch (Hold)	8 stimulus blocks: VVVVAAAA (AAAAVVVV)
8	Supplementary activity	Stroop task (ego-resiliency questionnaire, creativity questionnaire)

Table SM1. Experimental design, showing the eight stages in an experimental session. The order of the following were counterbalanced across participants: a) modality ordering of stimulus blocks, VVVVAAAA or AAAAVVVV, b) biased test conditions Hold/Switch in stages 5 and 7, c) supplementary task order ego-resiliency/creativity/Stroop in stages 4, 6 and 8.

Participants

A total of 51 adults participated in this study. The study was run at two separate locations (Hungary: Research Centre for Natural Sciences of the Hungarian Academy of Sciences (RCNS), 31 adults, 21 females, $M_{\text{age}} = 21.48$, $SD_{\text{age}} = 2.08$; U.K.: University of Plymouth (UoP), 20 adults, 13 females, $M_{\text{age}} = 21.5$, $SD_{\text{age}} = 3.05$).

Training

Visual Task

Participants were instructed to report LEFT if they perceived the front face of the rotating structure-from-motion sphere moving leftwards, and RIGHT if they perceived the front face of the rotating sphere moving rightwards. It is also possible to perceive two half-spheres, moving in opposite directions^{11,12}; participants were instructed to report COMBINED if they perceived this possibility.

These three interpretations were demonstrated to participants using disambiguated examples. LEFT (RIGHT) was disambiguated as explained before by reducing the luminance of the right-(left-) ward moving dots. The COMBINED interpretation was disambiguated with coloured dots; all of the dots moving leftwards were coloured green and those moving rightwards, yellow. The “Enter”, “Shift” and “Ctrl” keys located on the right-hand side of a standard computer keyboard were used as response keys, with key-response assignment counterbalanced across participants; see Figure SM3.

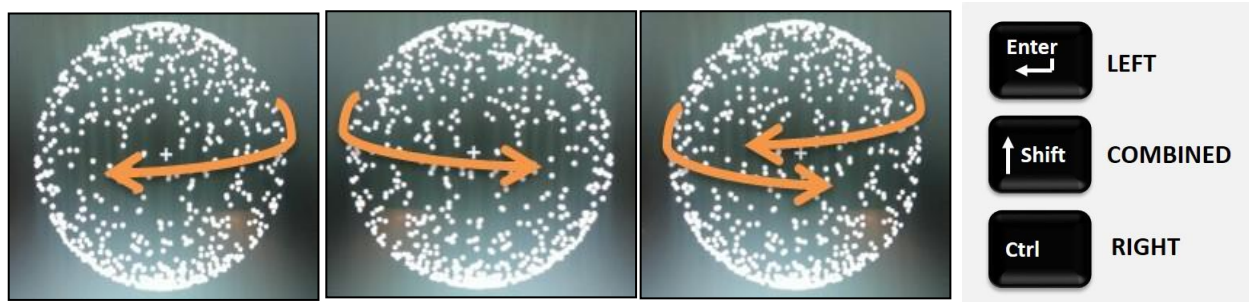


Figure SM3. Mnemonics and key assignments for categorising the ambiguous structure-from-motion stimulus.

Auditory Task

The tone sequence consisting of a repeating LHL_ pattern can be perceived in different ways; see Figure SM4. Participants were instructed to respond INTEGRATED, if they perceived all tones as belonging together, and SEGREGATED if they perceived the tones separating into two streams of sounds, one containing only high the other only low tones. It is also possible to perceive the tone sequence with the H tones and some of the L tones in one stream and the other L tones in another stream; LH__ with __L_ or _HL_ with L____^{13,14}. Participants were also told about these possibilities and instructed to report COMBINED if they perceived the tone sequence in this way.

These three interpretations were demonstrated to participants using disambiguated examples. INTEGRATED (SEGREGATED) was disambiguated as explained before by reducing (increasing) the frequency difference between the L and H tones. To demonstrate the COMBINED percept, participants were presented with examples in which the intensity and timbre of the background stream (__L_ or L____) was modified (with frequency difference 4 semitones); intensity was reduced by 18dB, timbre was changed by adding harmonics 2-8 (with equal weight) to the fundamental. The corresponding mnemonics shown in Figure SM3 were used by way of explanation and later as reminders. The “Enter”, “Shift” and “Ctrl”

keys located on the right-hand side of a standard computer keyboard were used as response keys, with key-response assignment counterbalanced across participants.

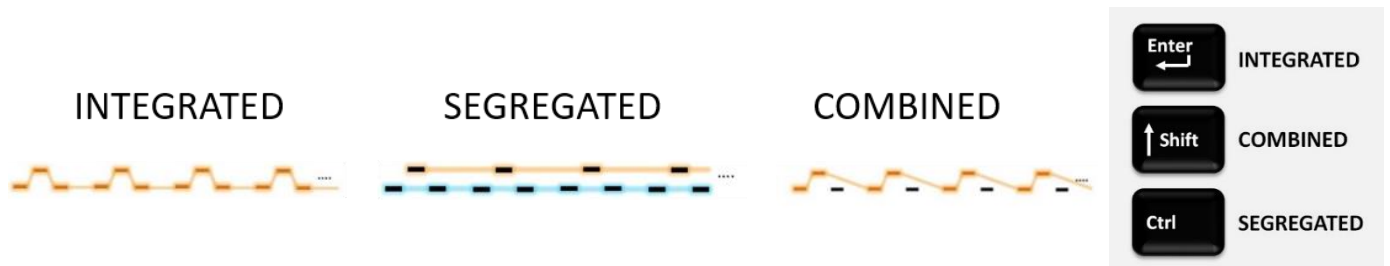


Figure SM4. *Mnemonics and key assignments for categorising the ambiguous tone sequences.*

Training and testing procedures were the same as those described for the experiment in the main paper.

Results for Experiment 2

Condition and modality

The influence of the attentional manipulation and modality on the average number of switches was assessed using a 2 (modality: visual, auditory) x 3 (condition: Neutral, Hold, Switch) repeated-measures analysis of variance (rmANOVA), with Greenhouse-Geisser sphericity correction. The main effect of condition was significant ($F(2,56) = 35.841, p < .001, \eta^2_{\text{partial}} = .561$). This shows that participants were able to bias their perception according to task instructions. Neither the effect of modality ($F(1,28) = 3.425, p = .078, \eta^2_{\text{partial}} = .109$) nor the modality/condition interaction ($F(2,56) = 2.101, p = .137, \eta^2_{\text{partial}} = .070$) were significant (Figure SM5). Thus, participants switched similarly across modalities and the effect of

attentional bias was similar for the two modalities.

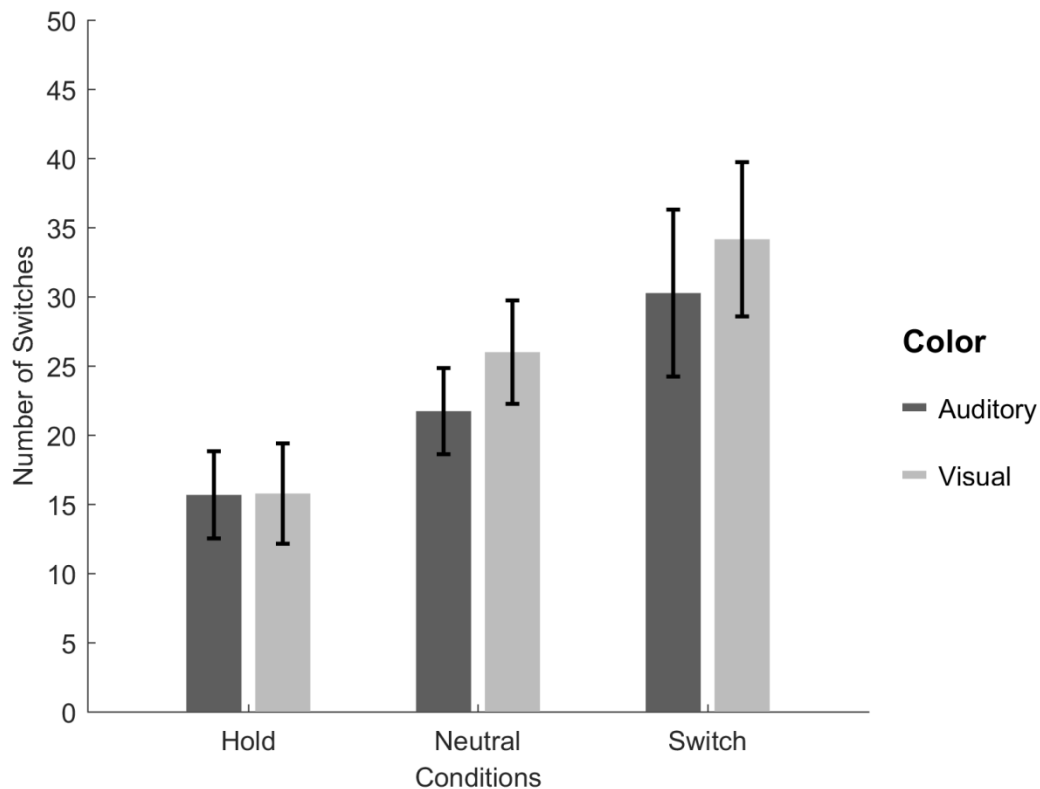


Figure SM5. Mean number of perceptual switches in each condition and modality. Error bars indicate 95% confidence intervals.

While the categories used in the first experiment remained dominant, participants reported all three perceptual alternatives; see Figure SM6 for the mean proportions of each.

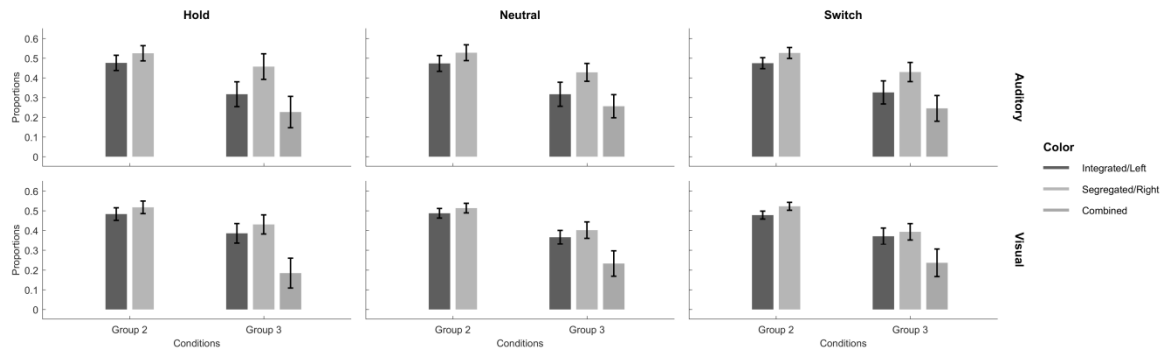


Figure SM6. Mean proportions for each perceptual category in each condition and modality.

Error bars indicate 95% confidence intervals.

Correlations across modalities

Cross-modal relationships between the number of switches were tested with Pearson correlations separately for each condition (Figure SM7). Correlations between the two modalities were significant in the Neutral ($r(29) = .396, p = .034, CI_{95} = .034-.666$), Hold ($r(29) = .620, p < .001, CI_{95} = .327-.804$), and Switch conditions ($r(29) = .621, p < .001, CI_{95} = .330-.805$). The correlation coefficients observed for the Hold ($z = -1.104, p = .270$) and Switch ($z = -1.114, p = .265$) conditions did not differ from the Neutral condition. No significant correlations were found between the number of switches in the Neutral condition and measures in the creativity, ego-resiliency, and Stroop tasks.

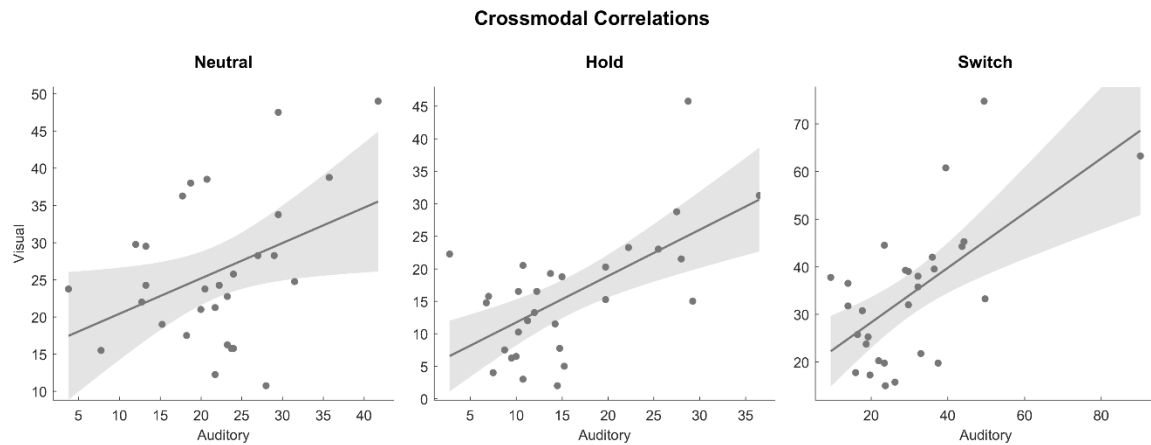


Figure SM7. Correlations in the number of perceptual switches across modalities, separately for each condition; 95% confidence intervals of the regression line indicated by shading.

Individual consistency

To explore individual consistency in switching across modalities, percepts were first reorganized into dominant/middle dominant/non-dominant categories (i.e. percepts were relabeled block-by-block according to their dominance to allow comparisons between the two modalities). Participant transition matrices⁸ were then constructed from the auditory and visual Neutral condition data. Intra-modal consistency was measured as the Kullback-Leibler (K-L)¹⁵ divergence between participants' auditory and visual transition matrices. Inter-participant consistency was measured by comparing the K-L distances between a participant's transition matrices and the transition matrices of all other participants. The distributions of intra-modal and inter-participant distance measures were compared using a left-tailed Wilcoxon's Rank Sum test. (One-sided significance testing was chosen, because the hypothesis was that participant intra-modal distances should be smaller than inter-participant distances). The result of the test ($z = -0.509$, $p = .306$) indicates that participants' perceptual switching behaviour was not more similar across the two modalities ($M = .146$,

$CI_{95} = .077-.216$) than the variation across participants ($M = .181$, $CI_{95} = .168-.192$). In short, in contrast to the first experiment, participants did not respond consistently within and across modalities.

Comparison of the distributions of phase durations across modalities

Raw phase durations from the Neutral condition only were pooled across participants separately for each modality. First, we tested whether the distribution of the phase durations was gamma or lognormal. Examination of Q-Q-plots⁶ indicated that the lognormal distribution fits the data better than the gamma distribution (Figure SM8).

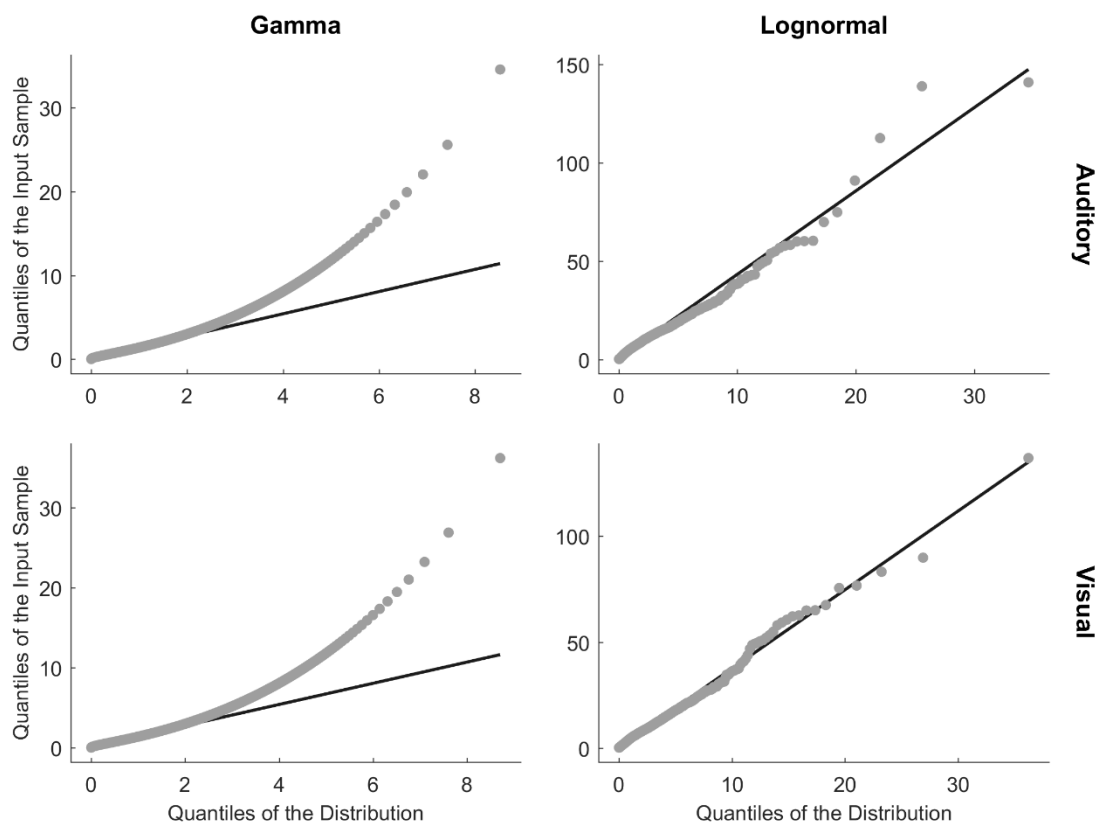


Figure SM8. QQ-plots of gamma (left) and lognormal (right) distributions for phase durations from the Neutral conditions in the auditory (upper row) and visual (lower row) modalities.

Phase distributions from the two modalities were first compared to each other using a Two-Sample Kolmogorov-Smirnov test. The result indicates that auditory and visual distributions were significantly different from each other ($D = 0.102$, $p = .003$). Second, the mu and sigma parameters of the lognormal distributions were calculated for phase durations separately for the auditory and visual modalities with 95% confidence intervals (Figure SM9).

Conversely to what was observed in the first experiment, the confidence intervals of the sigma parameter overlap across the two modalities and the confidence intervals of the mu parameter do not. This shows that although phase durations in the auditory and visual modalities can both be described by the same type of distribution (log-normal), the details of the distributions are different.

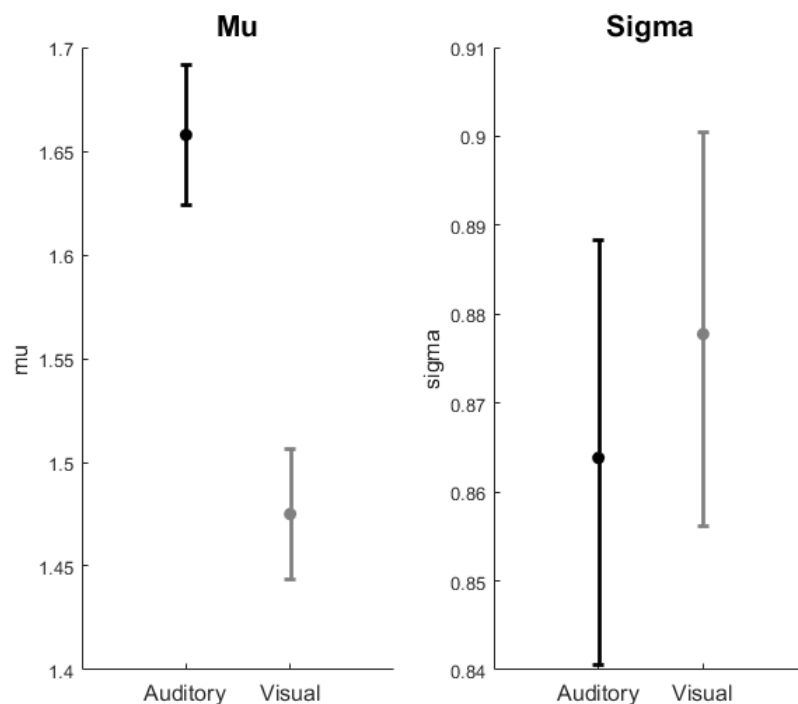


Figure SM9. *Mu (left) and Sigma (right) parameters of the lognormal distribution with 95% confidence intervals. In both subplots, the auditory modality is on the left side in black, and visual is on the right in grey.*

Correlations between phases

The relationships between successive phase durations (i.e. between the sequences of perceptual dominance durations) were tested with a mixed-level linear regression where participant identity was included as a random effect. Raw phase durations from the Neutral condition were \log_{10} -corrected in accordance with their log-normal distribution. This allowed us to meet not only the normality but also the linearity and heteroscedasticity assumptions of the test. Similarly to the individual consistency analysis, percepts were relabeled based on their overall duration in a block-by-block basis as Dominant (having the highest phase duration in a block), Non-dominant (having the lowest phase duration in a block), and Middle Dominant (the one between the Dominant and Non-dominant categories). Correlations were tested in both modalities for only one lag for all possible combinations of the Dominant/Middle Dominant/Non-dominant categories. The same transitions (D/MD, MD/D, ND/D) were significant in both modalities (Table SM2). Further, the R^2 , AIC, and BIC measures indicate a better model fit in the auditory than the visual modality.

Modality	Transition	N	R^2	AIC	BIC	Unstandardized b	t	r
Auditory	D/MD	668	13.92%	406.88	424.90	.174 (.102-.246)	4.759***	.373
	D/ND	271	0.81%	227.15	241.56	.085 (-.027-.198)	1.489	.090
	MD/D	680	12.93%	415.34	433.43	.185 (.112-.258)	4.969***	.360
	MD/ND	188	2.73%	152.04	164.99	.156 (.022-.291)	2.295*	.165
	ND/D	257	2.79%	230.07	244.27	.167 (.046-.288)	2.717**	.167
	ND/MD	198	0.56%	189.00	202.15	.082 (-.071-.235)	1.057	.075
Visual	D/MD	882	12.89%	640.07	659.20	.153 (.090-.216)	4.774***	.359

	D/ND	322	17.56%	212.13	227.23	.054 (-.042-.150)	1.111	.419
	MD/D	892	13.95%	674.93	694.11	.181 (.114-.248)	5.302***	.374
	MD/ND	230	28.47%	157.55	171.30	.028 (-.086-.142)	0.491	.534
	ND/D	327	1.24%	296.85	312.01	.118 (.003-.232)	2.022*	.111
	ND/MD	223	12.93%	170.20	183.83	-.019 (-.153-.114)	-0.286	.360

Table SM2. Relationship between successive phases in the auditory and visual modalities.

“Transition” refers the Dominant/Non-Dominant (D/ND), Dominant-Middle Dominant (D/MD), Middle Dominant/Dominant (MD/D), Middle Dominant/Non-dominant(MD/ND), the Non-Dominant/Dominant (ND/D), and Non-Dominant/Middle Dominant (ND/MD) transitions. R^2 refers to the explained variance of the model, whereas AIC and BIC refer to the Akaike or Bayesian Information Criterion, respectively. “Unstandardized b ” refers to the slope of the model with CI_{95} values included in parenthesis. “ t ” refers to the t -test examining the slope’s difference from zero and asterisks are indicating the level of significance (*** $p < .001$, ** $p < .01$, * $p < .05$). “ r ” refers to the correlation coefficient between the two phases estimated from the R^2 .

Conclusion

The results from the second experiment were broadly consistent with those of first experiment. However, participants found the auditory three-alternative task far more difficult than the visual one, as evidenced by the number of participants incorrectly categorising the disambiguated segments appended to the end of the test blocks. This difference may have caused some of the differences observed in the cross-modal comparisons.

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